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MEMORANDUM REPORT NO. 2703

QUASI-STATIC TENSILE STRESS STRAIN CURVES--II, ROLLED HOMOGENEOUS ARMOR

Ralph F. Benck

November 1976

USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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The modulus of elasticity, shear modulus, Poisson's ratio, yield and ultimate tensile strength at 22°C are reported for 1/2, 1 1/2, and 4-inch thick rolled homogeneous armor (RHA) plate. Specimens were taken at 3 orthogonal orientations from each plate. The effect of temperature from 22° to 800°C on the elastic constants is also reported for a specimen of 4-inch RHA.

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I. INTRODUCTION

The tests reported were conducted as part of the Core Materials Program of the Solid Mechanics Branch of the Terminal Ballistics Laboratory. This report is the seventh[1-6] in a series which present the results of tests designed to characterize the material properties of armor and kinetic energy penetrators. This data will be useful in the design of armored vehicles and projectiles, and can be used as input for computer codes modeling penetration processes.

This report presents the results of quasi-static tensile and sonic elastic moduli tests of 1/2, 1 1/2, and 4-inch thick plates of rolled homogeneous armor (RHA). Specimens for this study were obtained from three orthogonal orientations in each thickness of plate such that the axial direction of the specimen was: (1) Parallel to the rolling direction of the plate, (2) Perpendicular to the rolling direction of the plate, and (3) Through the thickness of the plate. The results include the modulus of elasticity, Poisson's ratio, yield and ultimate tensile strengths and engineering and true stress strain curves.

The alpha phase Hugoniot of this same batch of RHA has also been studied and is reported elsewhere[7].

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[1] *E. A. Murray, Jr. and J. H. Suckling, BRL Memorandum Report #2399, "Quasi-Static Compression Stress-Strain Curves--I, 1066 Steel", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, January 1974.* (AD #922704L)

[2] *E. A. Murray, Jr., BRL Memorandum Report #2589, "Quasi-Static Compression Stress-Strain Curves--II, 7039 Aluminum", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1976.* (AD #B009646L)

[3] *R. F. Benck and E. A. Murray, Jr., BRL Memorandum Report #2480, "Quasi-Static Compression Stress-Strain Curves--III, 5083-H131 Aluminum", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, May 1975.* (AD #B004159L)

[4] *R. F. Benck, G. L. Filbey, Jr. and E. A. Murray, Jr., BRL Memorandum Report in publication, "Quasi-Static Compression Stress-Strain Curves--IV, 2024-T3510 and 6061-T6 Aluminum Alloys", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.*

[5] *R. F. Benck and G. L. Filbey, Jr., BRL Memorandum Report in publication, "Elastic Constants of Aluminum Alloys, 2024-T3510, 5083-H131 and 7039-T64 as Measured by a Sonic Technique", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.*

[6] *R. F. Benck and D. A. DiBerardo, BRL Memorandum Report #2587, "Quasi-Static Tensile Stress-Strain Curves--I, 2024-T3510 Aluminum Alloy", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1976.* (AD #B009639L)

[7] *G. E. Hauver, BRL Memorandum Report in publication, "The Alpha Phase Hugoniot of Rolled Homogeneous Armor", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.*

II. TEST PROCEDURES

The material properties of the RHA under test were determined via quasi-static tensile tests and sonic, natural resonant frequency measurements.

A. Quasi-Static Tests

The testing apparatus, procedures and data reduction regimen were essentially the same as previously reported[1,6]. The material for the specimens was sawed from the center portions of 18 by 18 inch slabs of RHA (Military Specifications MIL-S-12560B). The slabs were cut with an acetylene torch from larger pieces of RHA. The use of the center portion insured that the material for the specimens was located at least four inches from an edge so that edge effects possibly introduced by the cutting technique were avoided. The specimens that had their axes oriented (1) perpendicular and (2) parallel to the rolling direction of the 4-inch plate originated from three different levels within the plate (i.e. one specimen was from the approximate first inch of the plate, a second from the next inch and the third from the next inch down). No effort was made to differentiate which specimen came from which level of the original plate.

Specimens from each plate were metallographically examined to determine the rolling direction.

A listing of the various specimens and their orientations relative to the original pieces of RHA armor is presented in Table I. The specimens were 82.5mm long except for those from the 1/2 and 1 1/2 inch plates that were oriented in the through thickness direction. The "through" specimens from the 1 1/2-inch material had a circular cross section with an overall length of 38mm and a gage length of approximately 19mm. The cross section for the "through" specimens from the 1/2-inch RHA was rectangular. These specimens were 1.02mm thick, 4.34mm wide and 12.7mm long. The final preparation of these specimens was by spark planing both sides of a 3.18mm thick blank.

All the specimens, except for the 1/2-inch "through" orientation, were instrumented with high elongation transverse foil resistance strain gages. In addition, all of the specimens, except for the 1/2 and 1 1/2 "through" specimens were also instrumented with a 50 percent maximum strain extensometer (Instron Model G-51-12).

TABLE I

EXPERIMENTAL PARAMETERS

RHA Plate Thickness Inches	Specimen Orientation[a]	Specimen Type[b]	Strain Measurement Technique[c]
1/2	W	A	FG, E
	C	A	FG, E
	T	B	P
1 1/2	W	A	FG, E
	C	A	FG, E
	T	D	FG, PL
4.	W	A	FG, E
	C	A	FG, E
	T	A	FG, E

[a] W - Specimen axial direction, parallel to rolling direction of the plate
C - Specimen axial direction, perpendicular to rolling direction of the plate
T - Specimen axial direction through the thickness of the plate

[b] A - Std. 6.35mm diameter cylindrical specimen ASTM[8] E8, reduced section approximately 55mm in length
B - Flat specimen, 1.02mm thick, 4.34mm wide and 12.7mm long
D - Std. 6.35mm diameter cylindrical specimen, reduced section approximately 19mm in length

[c] FG - High elongation foil strain gages, 3.18mm gage length.
E - Extensometer, 25.4mm gage length
P - Photographic record, approximate 3mm gage length
PL - Photographic record, approximately 13mm gage length

[8] *ASTM E8-69, "Standard Methods of Tension Testing of Metallic Materials", Figure 8, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.*

Some specimens had a gage length too short for the extensometer (minimum gage length 25mm); in these cases the strain was computed from photographs taken during the tests. The photographic technique involved: (1) Scribing two horizontal lines across the specimen, (2) photographing the specimen as it was pulled, and (3) measuring the distance between scratch marks from the photographs. A 35mm still camera with fast black and white film (ASA 400) was used for these measurements. The extensometer and/or photographic techniques were needed because the foil gages generally failed prior to specimen fracture. The data from the foil gages were used for strain computations up to the strains at gage failure, the remainder of the strain history was supplied from the extensometer and/or photographic record.

All the specimens were pulled to fracture with cross head motion of 0.1mm/min except for the 1/2-inch "through" specimens where the cross head motion was 5×10^{2}mm/min.

The average temperature for the tests was $22.2 \pm 0.6^{\circ}C$ with relative humidity of 62 ± 6 percent.

The procedures used to calculate engineering stress and engineering strain were reported previously.[1] The RHA tensile specimens exhibited considerable necking before fracture. Therefore, for some of the tensile tests, along with the load and strain measurements, the diameter of the cylindrical specimens, in the region of fracture, was measured as a function of tensile load. This was done so that true stress and true strain could be determined. True stress is defined as the intensity of load per unit of actual area. True strain, ε_x, is given by:

$$\varepsilon_x = 2 \ln \frac{D_o}{D_f}$$

where Do = original diameter
D_f = instantaneous diameter

The values of D_f were determined from photographs taken during the tensile tests.

B. Sonic Measurements of Elastic Constants

The apparatus and experimental procedures for these tests have been reported previously.[5] The specimens, except for those from the through orientation, were nominally 152.4mm long, 9.52mm diameter rods machined from the same RHA plates and at the same orientations as used for the tensile tests. The modulus of elasticity, the shear modulus and Poisson's ratio of the RHA rods were determined at $22^{\circ}C$. In addition, the elastic constants of one specimen taken from the 0.5-inch plate, parallel to the rolling direction, were determined at approximately $50^{\circ}C$ intervals from 22° to $800^{\circ}C$.

III. RESULTS

The modulus of elasticity, E, the shear modulus, G, yield and ultimate strengths (Y and U, respectively) and Poisson's ratio, γ, for three RHA plate thicknesses and for three specimen orientations within each plate are presented in Table II. The yield strength is defined as that stress at which the specimens deviated 0.2 percent from proportionality of stress to strain.

The maximum length of the through specimen from the 1/2-inch plate was too short for meaningful sonic measurements. The only strain measurement technique used on the 1/2-inch specimens was photographic and was insensitive to low strains. Consequently, E is not reported for this specimen and the value of Y is probably only good to plus or minus 5 percent.

The density of all the RHA was 7.84×10^3 kg/m^3.

The plates showed a Rockwell hardness (on the C scale) of 37 for the 1/2-inch plates, 30 to 31 for the 1 1/2-inch plates and an average of 27 for the 4-inch plates. The hardness of the 4-inch plates varied from 23 to 29 with the faces being the hardest.[7]

Figure 1 presents the average engineering stress versus engineering strain curves for specimens such that their axial direction is oriented parallel to the rolling direction of the plate. The error bars on the figure represent plus or minus one standard deviation. Similar curves are presented in Figure 2 for specimens oriented with axis perpendicular to the rolling direction of the plate. Figure 3 presents engineering stress versus engineering strain curves of specimens oriented through the thickness of the plate. The curves shown in Figure 3 for the 1/2 and 1 1/2-inch plates are based on single determinations. The curve for the 4-inch plate is an average of two tests up to a strain of 11.5 percent but is based on only one test from 11.5 to 13.5 percent strain. There were two replications of both the 1/2 and 1 1/2-inch specimens but in each case only one of the stress-strain curves was of high enough quality to be included in this report. As mentioned above, the strain measuring system used for the 1/2-inch, through the thickness specimens was photographic and was insensitive to low strains. Therefore, the stress-strain curves for the 1/2-inch specimens (Figures 3 and 4) are probably not accurate at strains less then one percent. At strains greater than one percent, the curves are a good representation of the stress-strain behavior of the material.

Figures 1-3 present stress-strain curves as a function of RHA plate thickness. Figures 4-6 present the same data as a function of specimen orientation. The "parallel" and "perpendicular" data for the 1 1/2 and 4-inch RHA were similar for each thickness and are shown in Figures 5 and 6 as single curves with a single set of error bars.

TABLE II

MATERIAL PROPERTIES OF 1/2, 1 1/2, AND 4-INCH RHA AT 22°C

RHA Plate Thickness	Specimen Orientation[a]		Modulus of Elasticity		Poisson's Ratio		Yield Strength	Ultimate Strength	Shear Modulus[b]	Strain at Fracture
			Quasi-static	Sonic[b]	Quasi-static	Sonic[b]				
Inch			GPa	GPa			MPa	MPa	GPa	%
1/2	W		204.1		.265		1038	1155		15.7
			202.7		.320		1016	1132		15.2
			201.0		.270		1005	1130		14.4
		Ave.	202.5	203.8	.285	.268	1020	1139	79.4	15.1
1/2	C		210.9		.296		1049	1172		12.2
			210.5		.270		1047	1164		14.8
			213.8		.273		1068	1186		13.3
		Ave.	211.7	205.0	.280	.274	1055	1174	79.5	13.4
1/2	T						770	986		9.8
							710	1054		5.7
		Ave.	---c	---c	---c	---c	740	1020	---c	7.8
1 1/2	W		204.9		.277		824	940		18.0
			204.9		.264		828	937		18.7
			204.1		.272		812	921		19.7
		Ave.	204.6	204.8	.271	.273	821	933	79.7	18.8
1 1/2	C		204.1		.267		822	940		17.2
			207.5		.265		831	962		17.0
		Ave.	205.8	205.3	.266	.272	826	951	79.9	17.1
1 1/2	T		200.0		.278		810	887		11.9
			202.8		.272		788	883		11.7
		Ave.	201.4	203.3	.275	.280	799	885	78.9	11.8

TABLE II (Cont'd)

MATERIAL PROPERTIES OF 1/2, 1 1/2, AND 4-INCH RHA AT 22°C

RHA Plate Thickness	Specimen Orientation[a]		Modulus of Elasticity		Poisson's Ratio		Yield Strength	Ultimate Strength	Shear Modulus[b]	Strain at Fracture
			Quasi-static	Sonic[b]	Quasi-static	Sonic[b]				
Inch			GPa	GPa			MPa	MPa	GPa	%
4	W		203.3		.270		700	861		22.3
			210.5		.270		702	863		21.5
		Ave.	206.9	205.7	.270	.271	701	862	80.2	21.9
4	C		202.8		.272		704	867		19.8
			213.3		.274		723	873		19.6
		Ave.	208.0	205.9	.273	.284	713.5	870	80.8	19.7
4	T		200.0		.275		644	784		13.5
			206.9		.272		658	804		11.5
		Ave.	203.5	203.8	.274	.266	651	794	80.5	12.5

a W - Specmen Axial Direction, Parallel to Rolling Direction of the Plate
C - Specimen Axial Direction, Perpendicular to Rolling Direction of the Plate
T - Specimen Axial Direction Through the Thickness of the Plate

b Results of Single Test

c Not Measured

The modulus of elasticity and the shear modulus of a specimen of RHA machined from a 4-inch plate, parallel to the rolling direction of the plate are presented as functions of temperature in Figure 10. Poisson's ratio for the same specimen as a function of temperature is presented in Figure 11.

Results of the chemical analysis of the three RHA plates are shown in Table III.

TABLE III

CHEMICAL ANALYSIS[a] OF RHA SAMPLES

Element	Weight Percent		
	1/2-Inch Plate	1 1/2-Inch Plate	4-Inch Plate
Carbon	0.22	0.26, 0.26	0.27, 0.27
Manganese	0.26	0.27	0.27
Phosphorus	0.001	0.001	0.001
Sulfur	0.015	0.008	0.008
Silicon	0.19	0.18	0.15
Nickel	3.15	3.04	3.47
Copper	<0.1	0.07	0.05
Chromium	1.06	1.07	1.37
Vanadium	<0.01	<0.01	<0.01
Molybdenum	0.15/0.30	0.10/0.25	0.10/0.25
Aluminum	0.03	<0.02	0.03
Titanium	None Detected	None Detected	None Detected

[a] Frankford Arsenal, Materials Laboratory, Technical Support Dir.

True stress versus true strain curves are presented in Figures 7 through 9 for 1/2, 1 1/2, and 4-inch RHA thicknesses and for 3 specimen orientations from each plate; the only combination not tested was the 1/2-inch thickness in the through direction. These curves are results of single determinations made for each thickness and orientation.

CONCLUSIONS

Material properties of 1/2, 1 1/2, and 4-inch thick RHA steel, sampled in three orientations within each plate, have been measured via quasi-static tensile tests and sonic measurements of the natural frequencies.

The results indicate that RHA is anisotropic, especially when comparing specimens oriented with their axis through the thickness of the plate to specimens whose axes were either oriented parallel or perpendicular to the rolling direction of the plate. The yield and ultimate strengths of through the thickness oriented specimens were 3.5 to 8 percent lower than were the other two orientations. The specimens oriented perpendicular to the rolling direction of the plate show consistent yield and ultimate strengths approximately one percent above specimens oriented parallel to the rolling direction of the plate.

It is concluded from the reproducibility shown that the results presented are an accurate partial description of the elastic and plastic properties of the RHA tested.

REFERENCES

1. E. A. Murray, Jr. and J. H. Suckling, BRL Memorandum Report 2399, "Quasi-Static Compression Stress-Strain Curves--I, 1066 Steel", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, January 1974. (AD #922704L)

2. E. A. Murray, Jr., BRL Memorandum Report 2589, "Quasi-Static Compression Stress-Strain Curves--II, 7039 Aluminum", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1976. (AD #B009646L)

3. R. F. Benck and E. A. Murray, Jr., BRL Memorandum Report 2480, "Quasi-Static Compression Stress-Strain Curves--III, 5083-H131 Aluminum", Ballistic Research Laboratories, Aberdeen Proving Ground, MD, May 1975. (AD #B004159L)

4. R. F. Benck, G. L. Filbey, Jr. and E. A. Murray, Jr. BRL Memorandum Report In Publication, "Quasi-Static Compression Stress-Strain Curves--IV, 2024-T3510 and 6061-T6 Aluminum Alloys", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

5. R. F. Benck and G. L. Filbey, Jr., BRL Memorandum Report In Publication, "Elastic Constants of Aluminum Alloys, 2024-T3510, 5083-H131 and 7039-T64 as Measured by a Sonic Technique", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

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7. G. E. Hauver, BRL Memorandum Report In Publication, "The Alpha Phase Hugoniot of Rolled Homogeneous Armor", Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

8. ASTM E8-69, "Standard Methods of Tension Testing of Metallic Materials", Figure 8, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

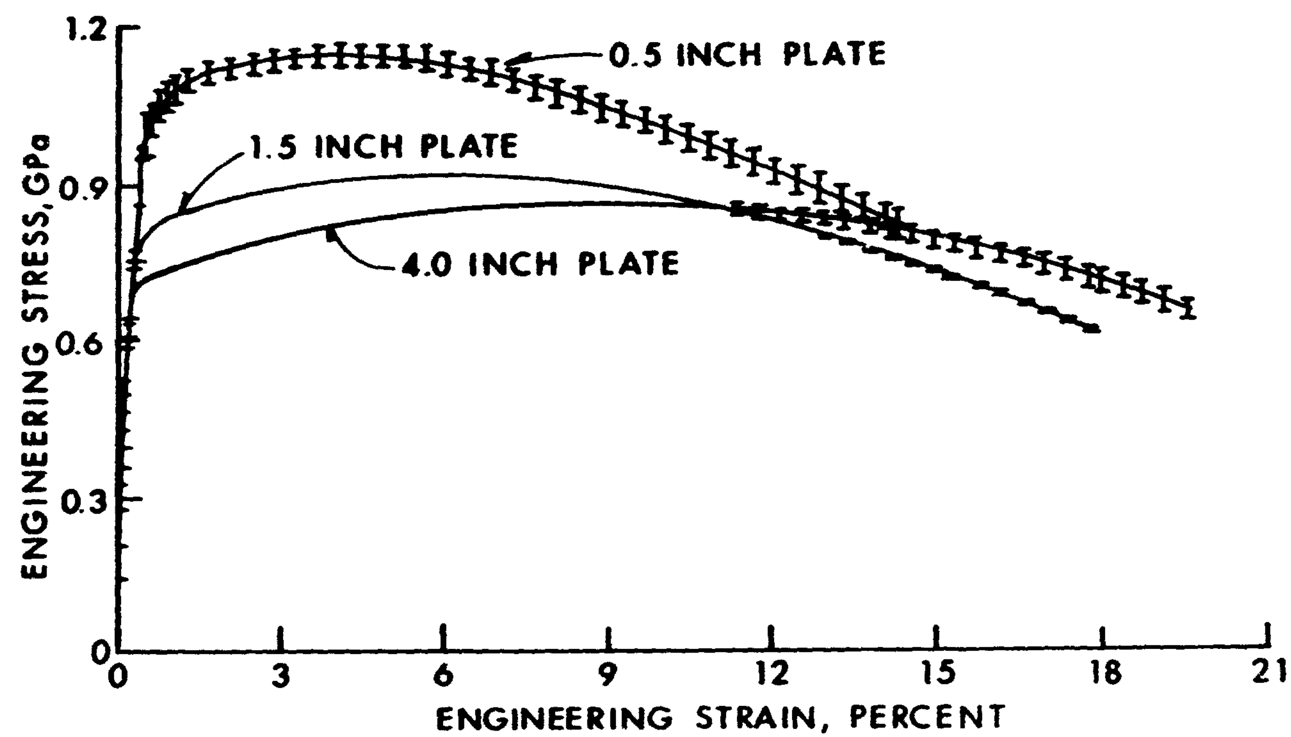

FIGURE 1: Engineering Stress vs. Engineering Strain for 1/2, 1 1/2, and 4-Inch RHA; Specimens Oriented with Axis Perpendicular to Rolling Direction.

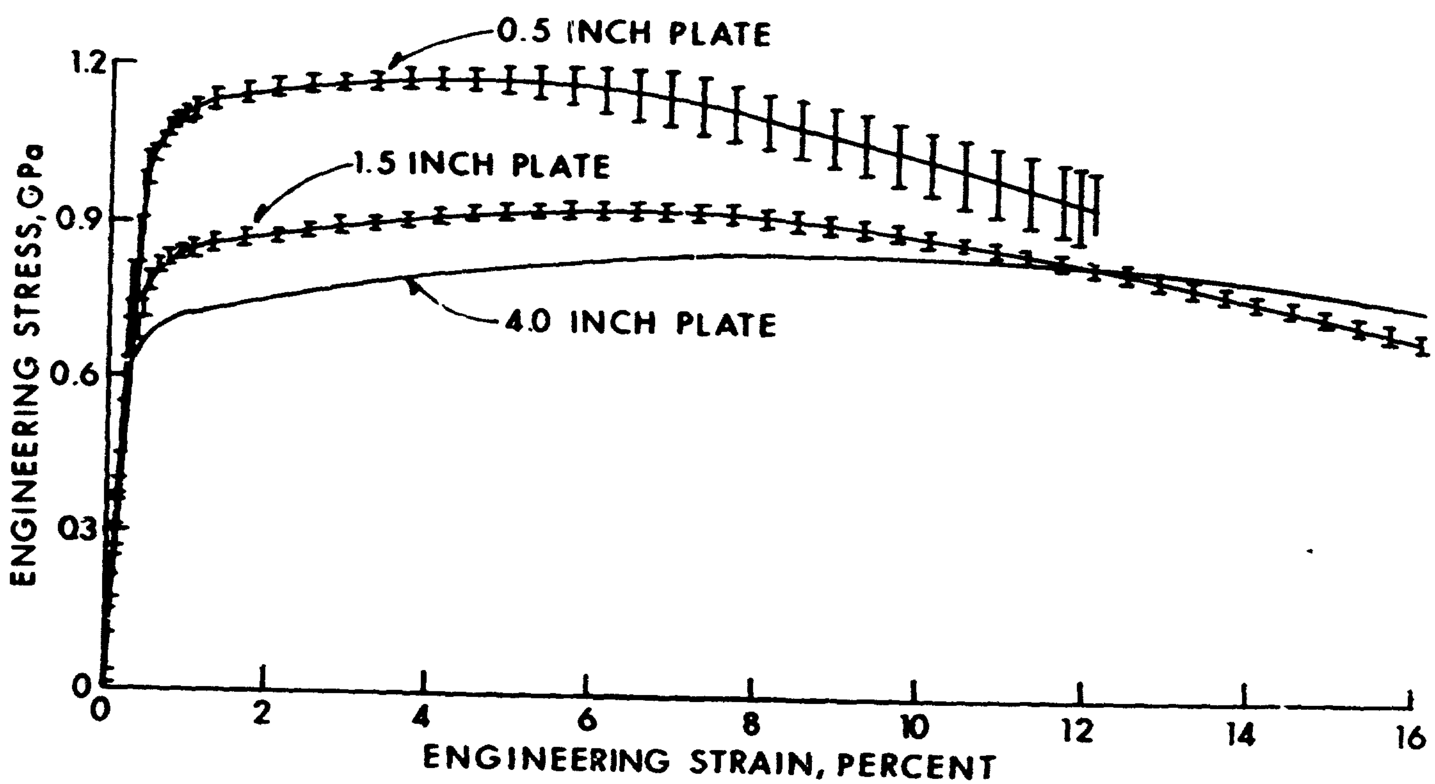

FIGURE 2: Engineering Stress vs. Engineering Strain for 1/2, 1 1/2, and 4-Inch RHA; Specimens Oriented with Axis Parallel to Rolling Direction.

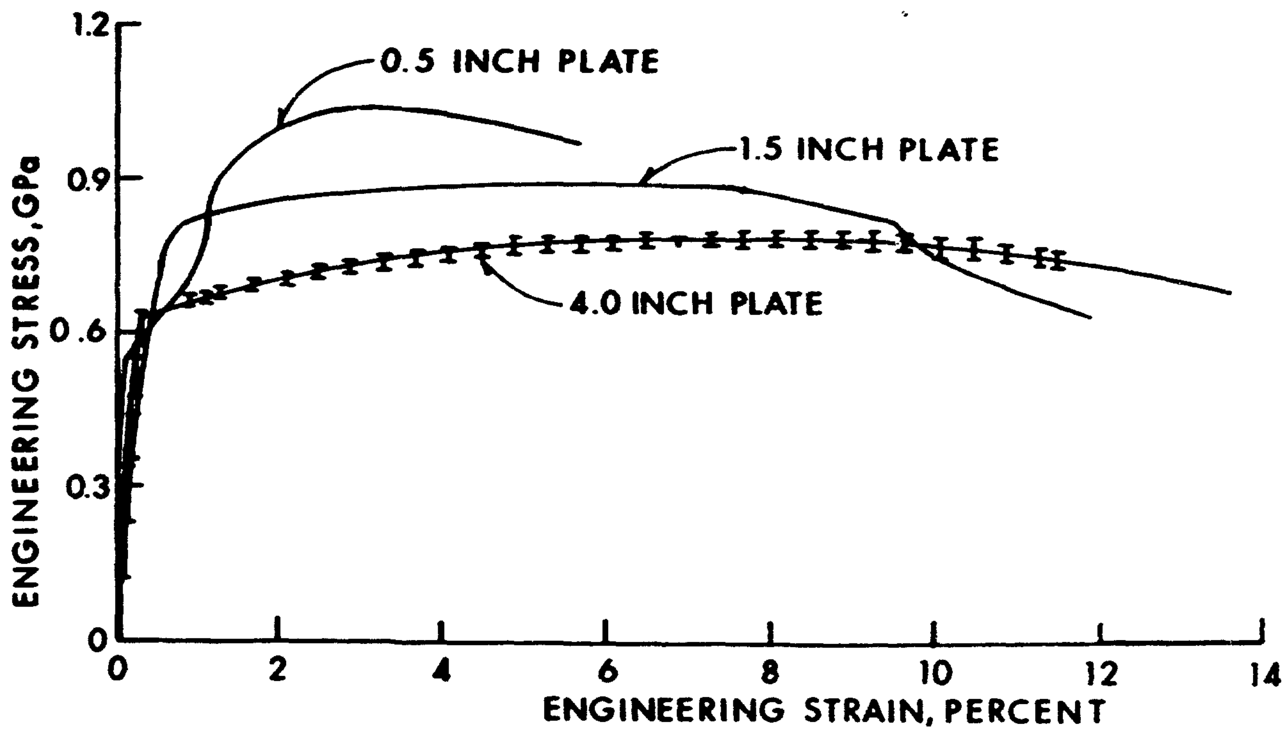

FIGURE 3: Engineering Stress vs. Engineering Strain for 1/2, 1 1/2, and 4-Inch RHA; Specimens Oriented with Axis Through the Plate.

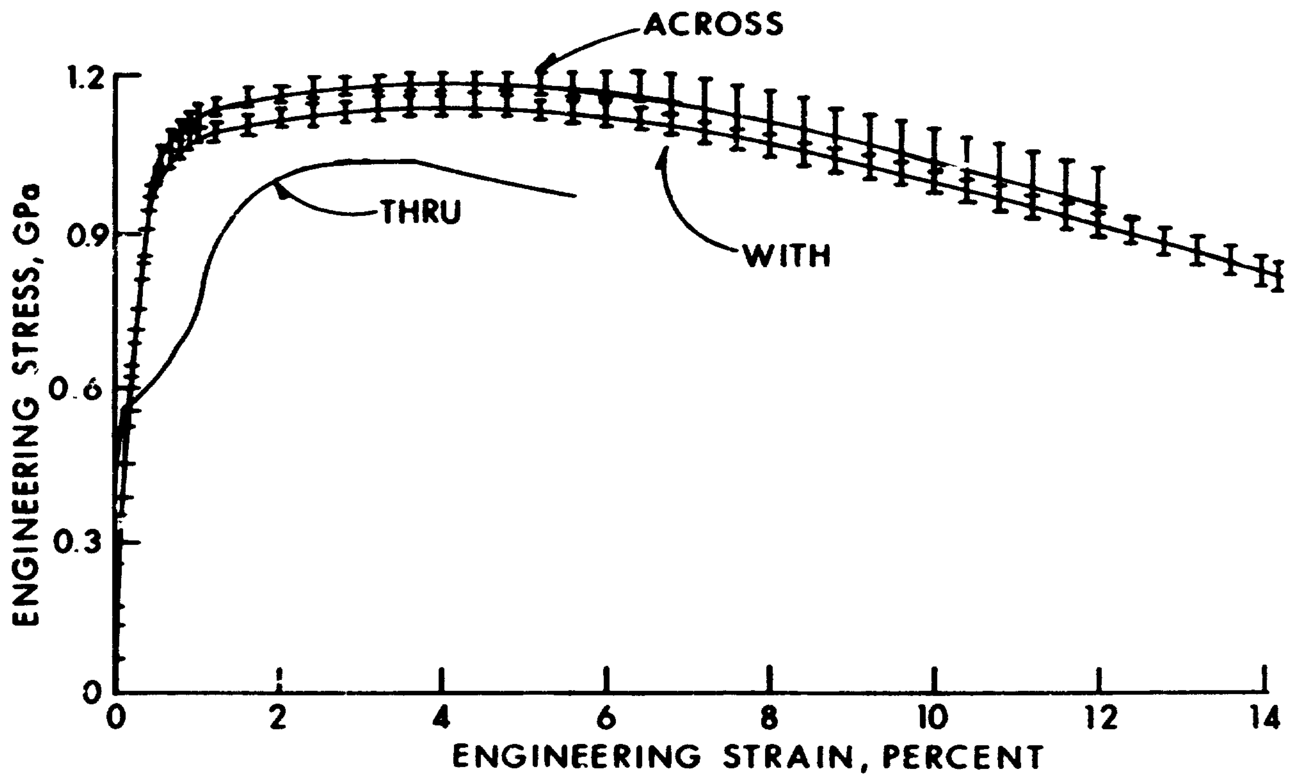

FIGURE 4: Engineering Stress vs. Engineering Strain for 1/2-Inch RHA Plate; Specimens Oriented with Axis (1) Parallel to Rolling Direction, (2) Perpendicular to Rolling Direction and (3) Through Plate Thickness.

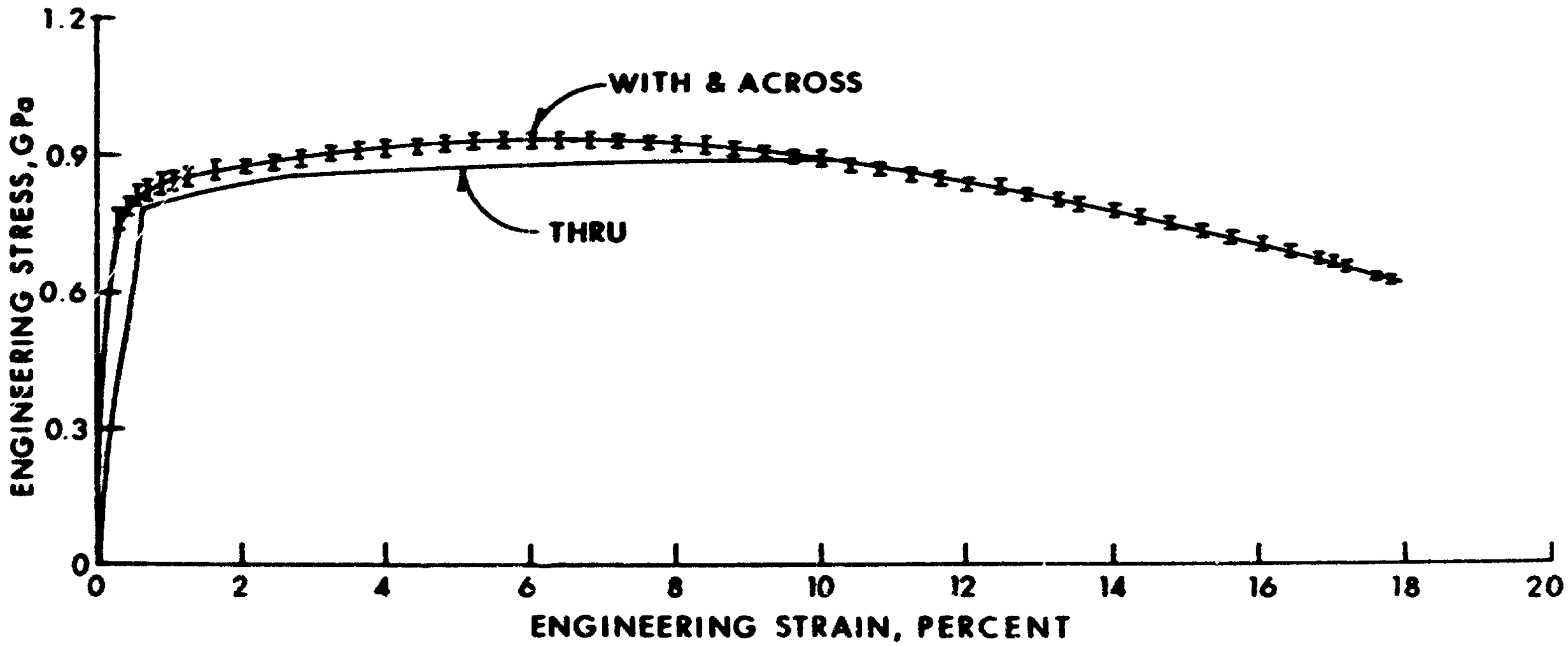

FIGURE 5: Engineering Stress vs. Engineering Strain for 1 1/2-Inch RHA Plate; Specimens Oriented with Axis (1) Parallel to Rolling Direction, (2) Perpendicular to Rolling Direction and (3) Through Plate Thickness.

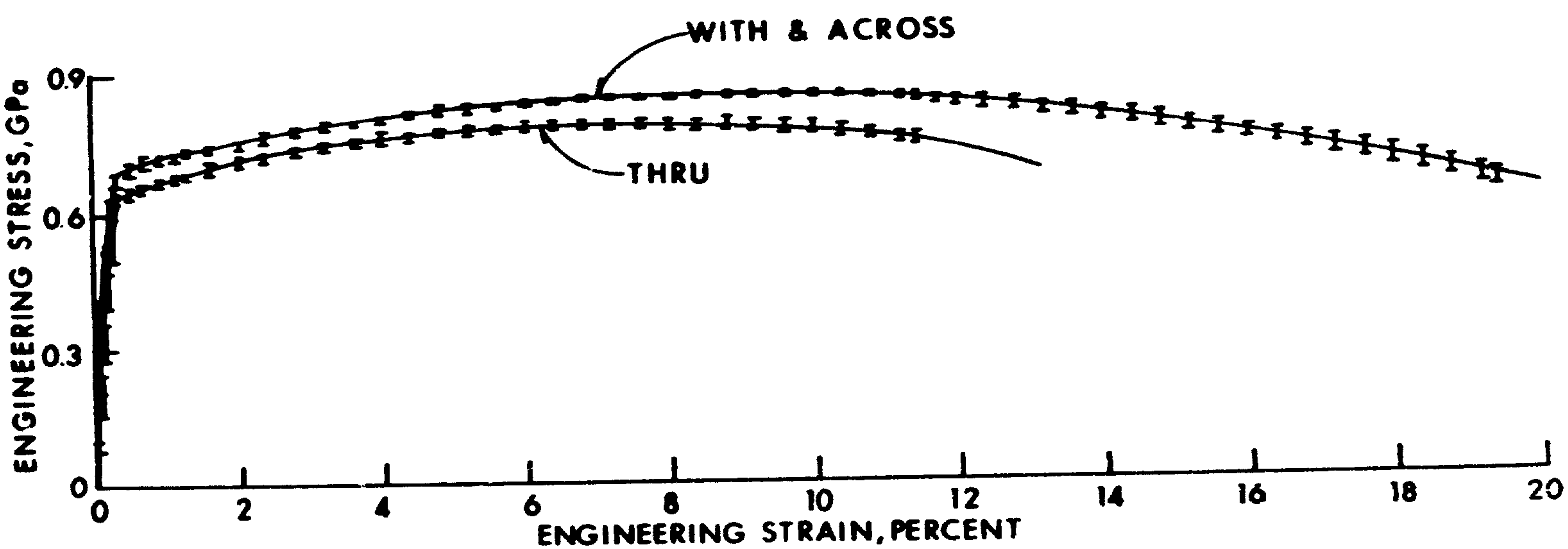

FIGURE 6: Engineering Stress vs. Engineering Strain for 4-Inch RHA Plate; Specimens Oriented with Axis (1) Parallel to Rolling Direction, (2) Perpendicular to Rolling Direction and (3) Through Plate Thickness.

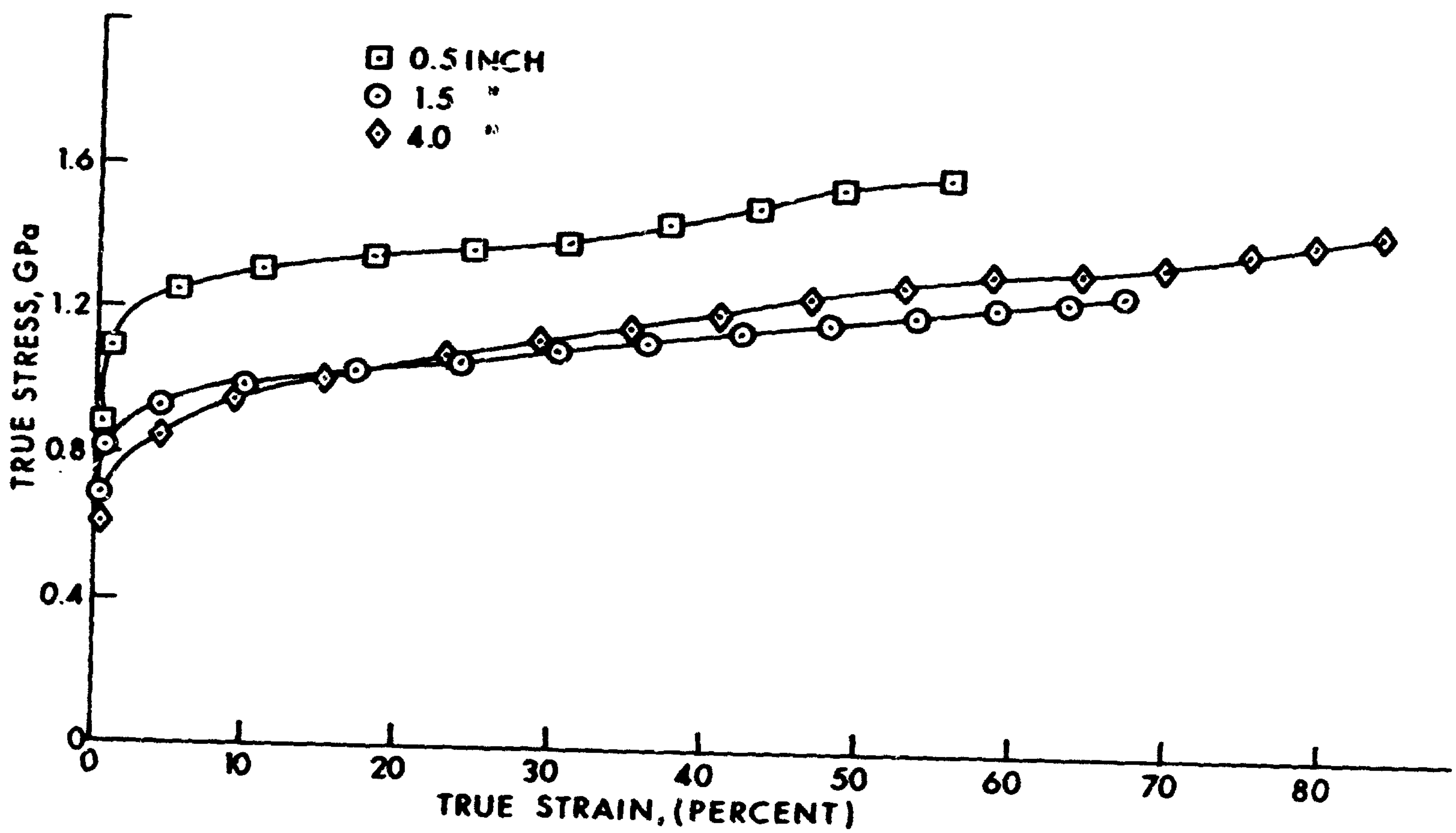

FIGURE 7: True Stress vs. True Strain for 1/2, 1 1/2, and 4-Inch RHA; Specimens Oriented with Axis Perpendicular to the Rolling Direction of the Plate.

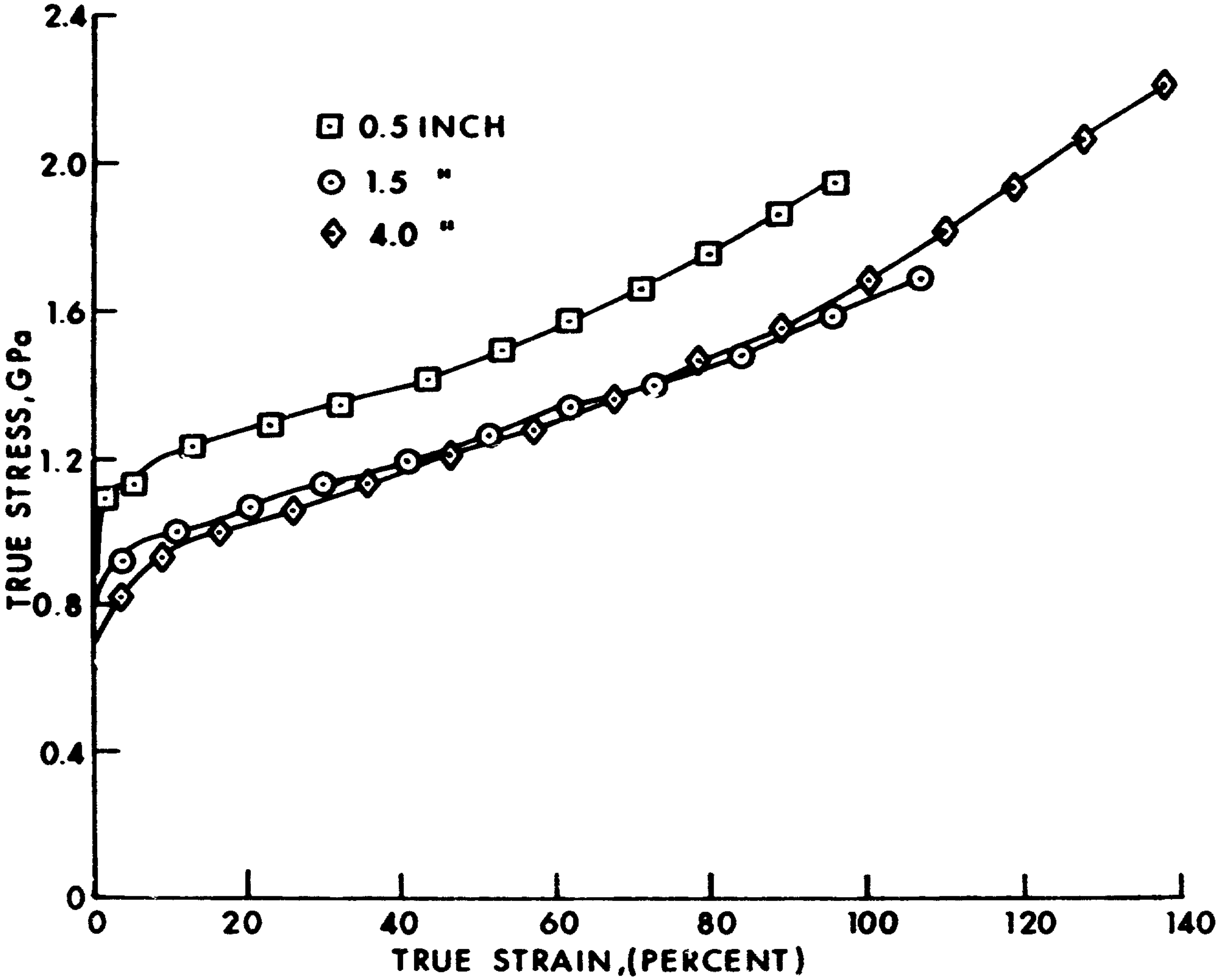

FIGURE 8: True Stress vs. True Strain for 1/2, 1 1/2 and 4-Inch RHA; Specimens Oriented with Axis Parallel to the Rolling Direction of the Plate.

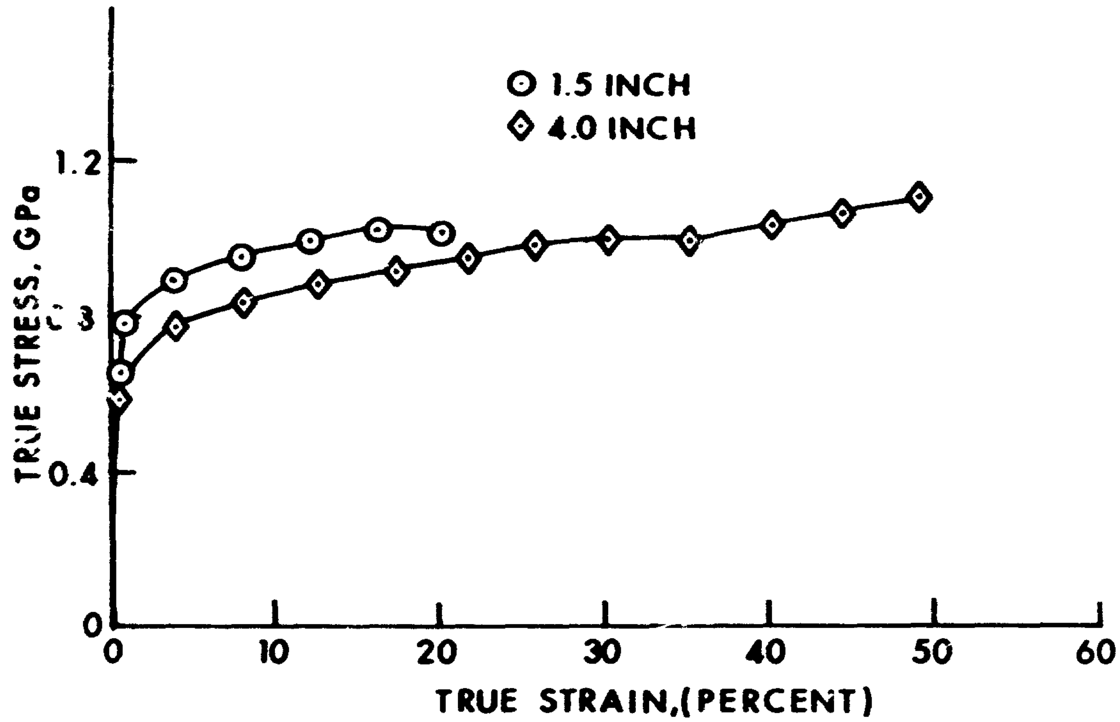

FIGURE 9: True Stress vs. True Strain for 1 1/2 and 4-Inch RHA; Specimens Oriented with Axis Through the Plate Thickness.

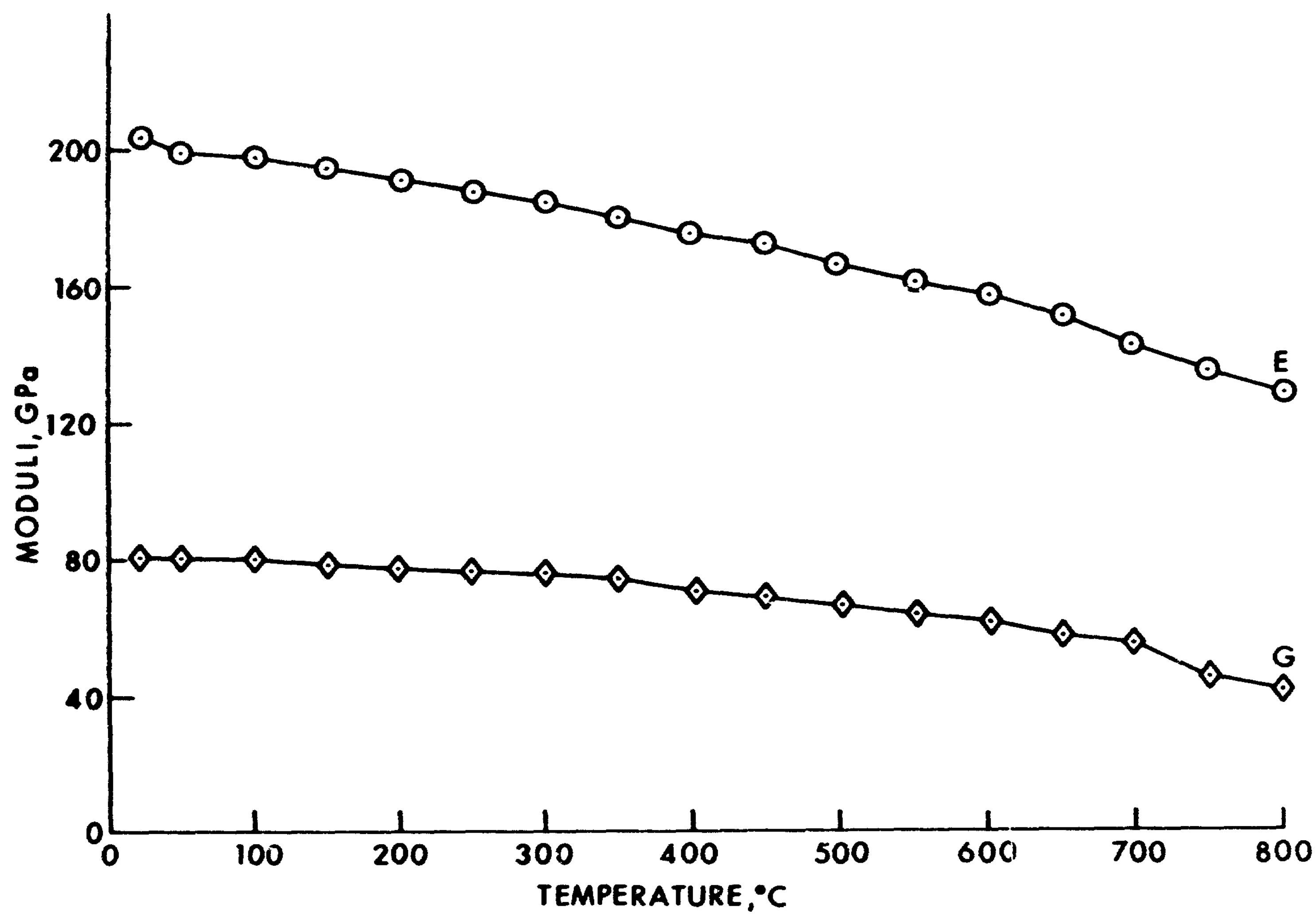

FIGURE 10: Moduli of Elasticity and Shear as Functions of Temperature for 4-Inch RHA; Specimen Oriented with Axis Parallel to the Rolling Direction of the Plate.

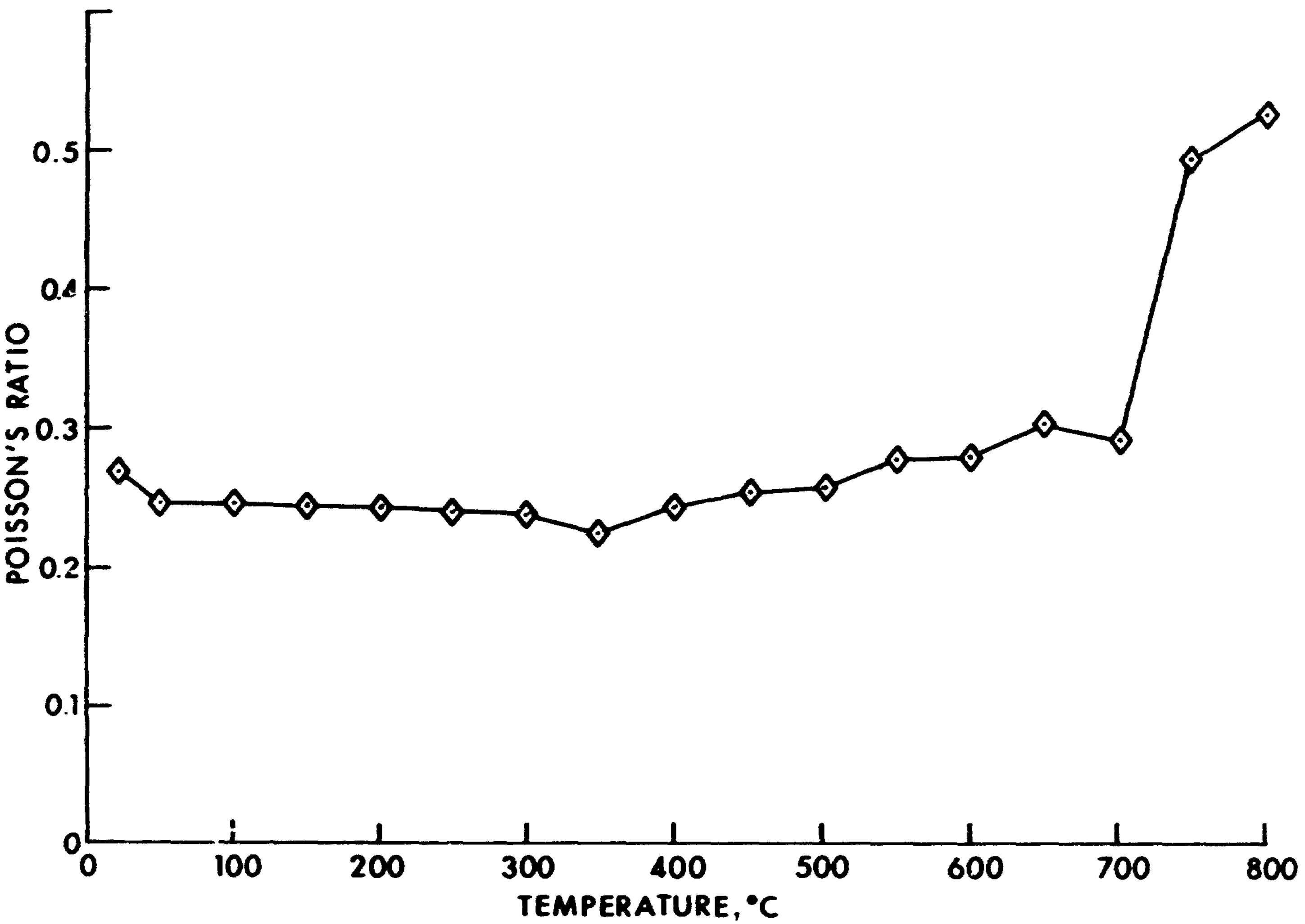

FIGURE 11: Poisson's Ratio as a Function of Temperature for 4-Inch RHA; Specimen Oriented with Axis Parallel to the Rolling Direction of the Plate.

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